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Analysis of the mechanical behavior of thin ice layers on structures including radial cracking and de-icing

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In this paper multiple radial cracking in thin ice layers is studied which occurs when applying mechanical de-icing systems to aircraft structures. Brittle crack propagation is investigated based on the example of an ice layer adhering to an aluminium plate under static and dynamic normal loading. The finite element method is used in combination with cohesive zones to study the influence of the ice layer thickness, the out-of-plane displacement, and the cohesive parameters on the radial cracking process as well as on the dynamic behavior and de-icing of the structure.

1. Introduction

The fracture process of a thin ice sheet which is subject to out-of-plane loading is characterized by multiple radial cracks that propagate from the center of the load, see Fig. 1. The type of loading strongly influences the crack pattern as well as the de-icing performance. In case of the quasi-static loading in Fig. 1a crack branching but no ice shedding can be detected, whereas in the case of dynamic impulse loading in Fig. 1b additional circumferential cracks occur and multiple ice segments detach from the structure. One of the major difficulties in the analyses of these cracking phenomena are the modeling of the brittle material behavior of each crack path as well as the mutual interference of the numerous crack paths.

A widely used method to predict fracture processes is the finite element method (FEM) which can for example be used in combination with the cohesive zone model (CZM) [2–7]. The crack path of the CZM is restricted to finite element boundaries, but apart from that, location and path are arbitrary and no pre-existing crack is required in order to predict the onset and propagation of a crack which is of great significance in this study. Since the CZM is a phenomenological approach which is independent of microstructural failure mechanisms, the model can be applied to all types of material including both ductile and brittle behavior [7]. Further advantages of the CZM are the ability to simulate multiple branching cracks as well as the requirement of only two model parameters [7,8]. However, it has to be mentioned that the CZM also has some limitations like its mesh dependency [8].

Further approaches to model fracture processes are the extended finite element method (XFEM), e.g. [9–11], as well as the discrete element method (DEM), e.g. [12–14].

The phenomenon of radial cracking in brittle materials has been subject to many research studies. Vandenberghe et al. [15] investigated the radial crack pattern of locally impacted brittle plates and developed a global scaling law for the number of radial cracks based on Griffith's theory of fracture. Another experimental study was performed by Döll [16] on the fracture

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Nomenclature

E	Young's modulus, GPa
G	energy release rate, J/m^2
n	number of elements, –
t	thickness, m
u	displacement, m
δ	cohesive (normal) separation, m
γ	cohesive tangential separation, m
ν	Poisson's ratio, –
σ	cohesive (normal) stress, MPa
τ	shear stress, MPa
τ	cohesive shear stress, MPa

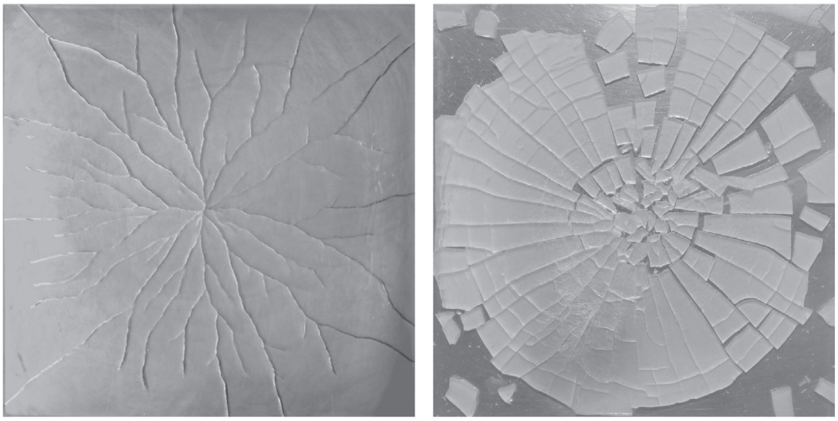
Subscript

Al	aluminium
c	critical
ice	ice
max	maximum
mean	mean
I	mode I
II	mode II

Abbreviations

CZM	cohesive zone model
FEM	finite element method

of glass which showed that crack branching depends on the maximum fracture velocity in the material and the strain energy release rate exceeding some critical value. There exists also an analytical approach by Dempsey et al. [17] which studies the progressive radial cracking of a clamped plate made of elastic brittle material. In their work a formulation is developed which does not only consider bending and stretching effects but also closure effects of the radial crack face contacts on the compressive side of the plate. Numerical investigations on crack branching using the CZM have been conducted for example by Xu and Needleman [18] who studied fast crack growth in a plane strain block made of brittle material with an initial central crack subjected to tensile loading. The two-dimensional block is meshed with triangular elements and they provide a solution for the node connectivity at the intersection of possible crack paths. Repetto et al. [19] present a two-dimensional FE model to simulate dynamic fracture of glass rods. Therein, they developed a new model of radial cracking and utilize a contact algorithm to allow for complex collisions of the fractured glass particles. A cohesive FE model to study fast crack growth in brittle solids has been developed by Camacho and Ortiz [20]. Their model includes contact, friction, plasticity, heat conduction as well as thermal coupling and was applied to spall tests and doubler cantilever beam tests as well as to pellet



(a) Quasi-static loading (b)Dynamic force impulse [1]

Fig. 1. Radial crack pattern.

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